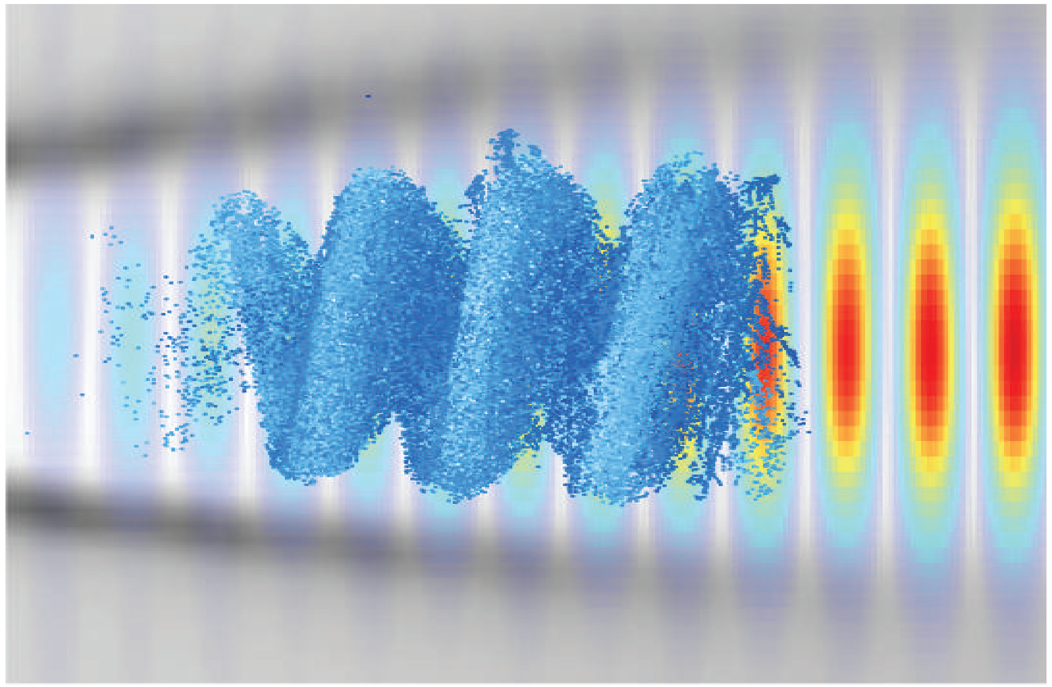
Exploiting lights momentum to boost laser wakefield accelerators towards high field physics

J.Vieira, J.L Martins, U. Sinha, M.Vranic, T. Grismayer, R.A. Fonseca, L.O. Silva

Instituto de Plasmas e Fusão Nuclear
Instituto Superior Técnico
Lisbon, Portugal

http://epp.ist.utl.pt[/jorgevieira]



GoLP/IPFN Instituto Superior Técnico

grupo de lasers e plasmas

INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

Contents

Generation of circularly/elliptically polarised betatron x-rays

Orbital angular momentum laser drivers for high gradient positron acceleration

Radiation reaction and pair production driven by ultra-intense lasers

Conclusions

Contents

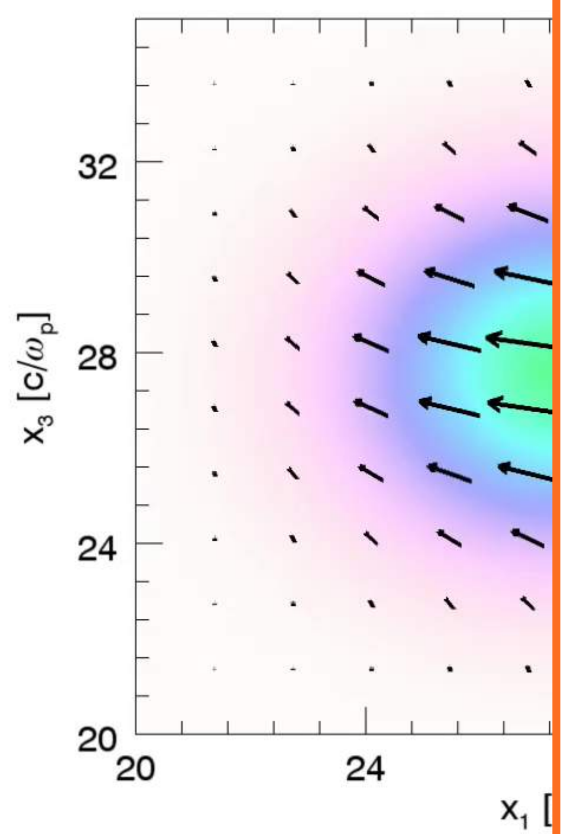
A compact plasma based circularly polarised light source

Just like any particle, light can also carry momentum

In addition to linear momentum, light also carries angular momentum

Circular pc

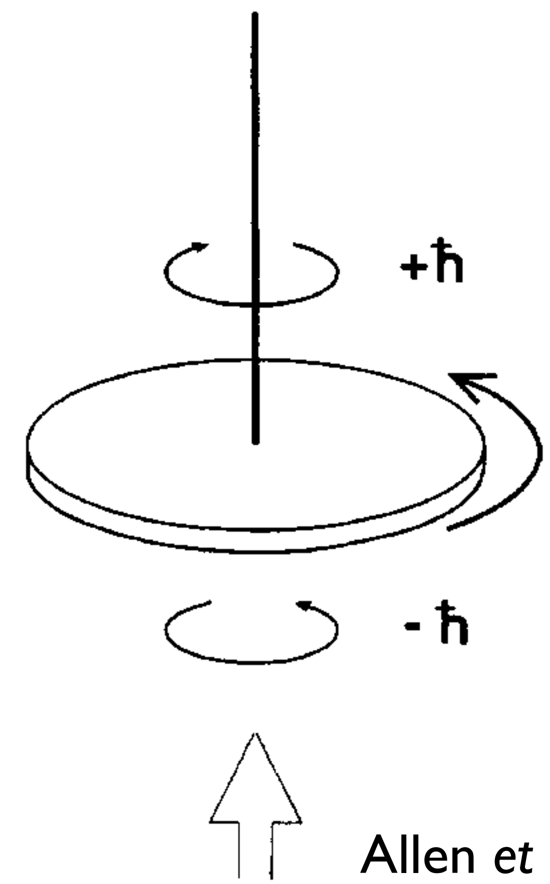
Transverse ve
circularly polarise



Assume two values: rig
left handed (spin -1)

Conservation of angular momentum

Beth's experiments showed that light's angular momentum exerted a torque on matter.



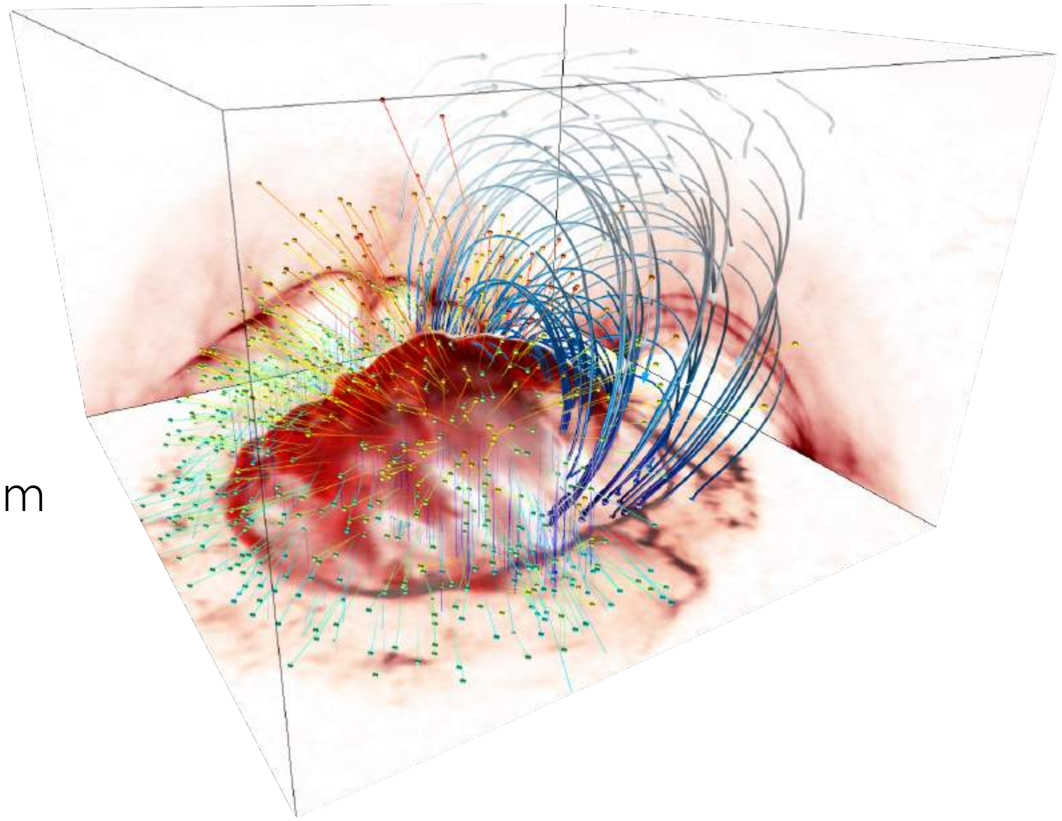
Allen *et al* PRA 1992

Can a circularly polarised laser driver exert a torque on relativistic electrons which in turn will produce circularly polarised x-rays?

Osiris 3.0

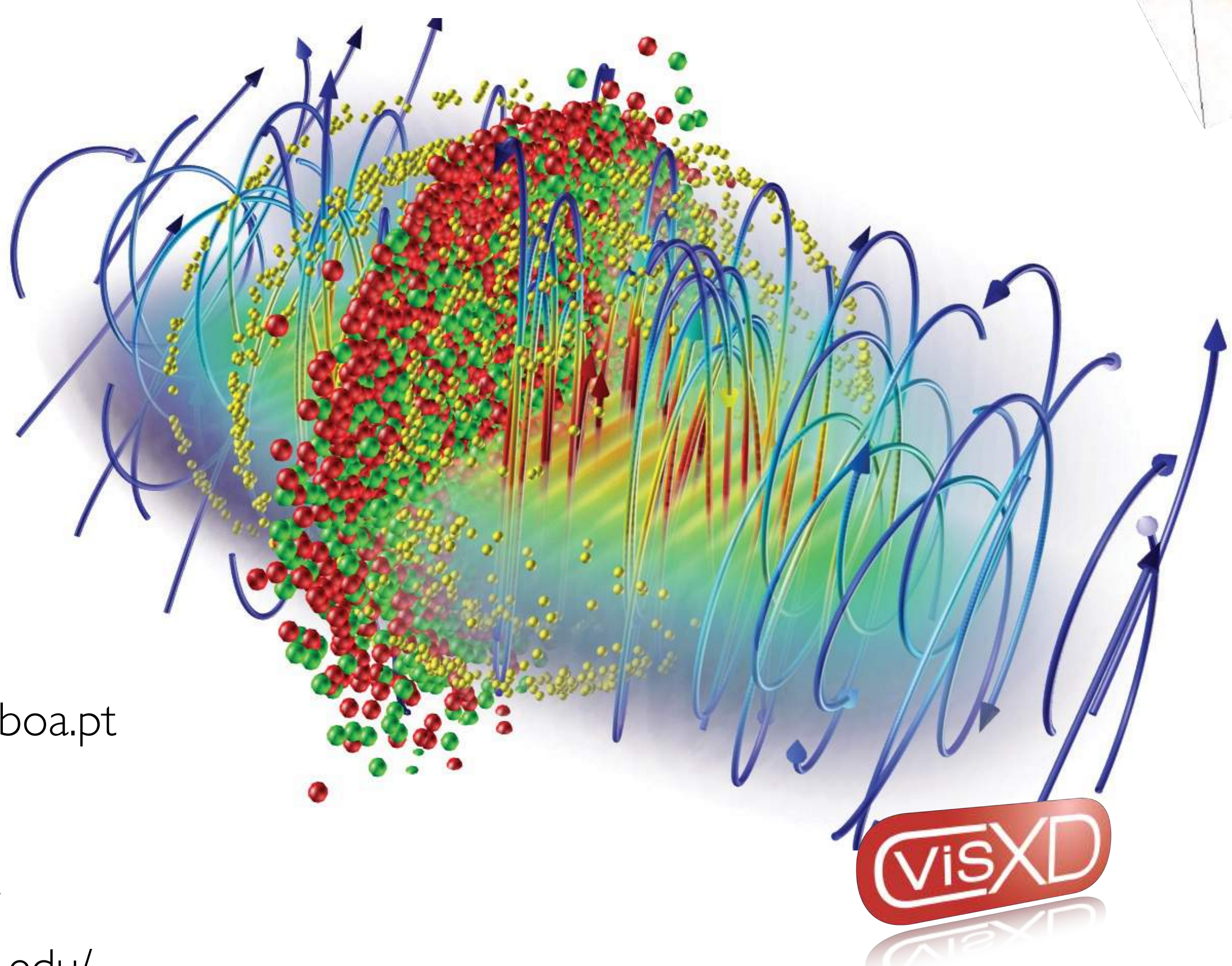
osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  - ⇒ UCLA + IST



TÉCNICO LISBOA

UCLA



code features

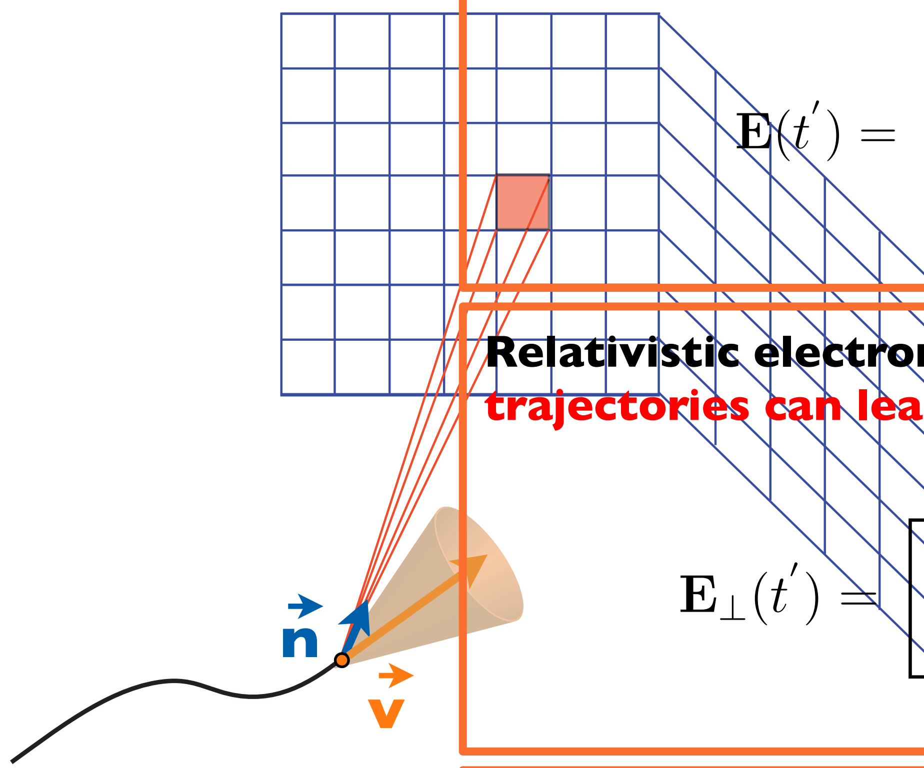
- Scalability to ~ 1.6 M cores
- SIMD hardware optimized
- Parallel I/O
- Dynamic Load Balancing
- QED module
- Particle merging
- GPGPU support
- Xeon Phi support

Ricardo Fonseca
ricardo.fonseca@tecnico.ulisboa.pt
Frank Tsung
tsung@physics.ucla.edu

http://epp.tecnico.ulisboa.pt/
http://plasmasim.physics.ucla.edu/

Helical betatron trajectories can lead to circularly polarised x-rays

jRa



- Massively parallel and optimal efficiency
- Space and time resolved spectra and total power
- Trajectory interpolation

J. L. Martins et al Proc. of SPIE **7359**, 73590V (2009)

Polarisation from relativistic charges

$$\mathbf{E}(t^{'}) = \left[\frac{e}{c} \frac{\mathbf{n} \times \left\{ (\mathbf{n} - \boldsymbol{\beta}) \times \dot{\boldsymbol{\beta}} \right\}}{(1 - \boldsymbol{\beta} \cdot \mathbf{n})^3 R} \right]_{\mathrm{ret}}$$

Relativistic electron far field: helical e- trajectories can lead to circular/elliptical X-rays

$$\mathbf{E}_{\perp}(t^{'}) = \left[\frac{e}{cR} \frac{\boldsymbol{\beta}_{\perp} \dot{\beta}_z - \dot{\boldsymbol{\beta}}_{\perp} (1 - \beta_z)}{(1 - \beta_z)^3} \right]_{\mathrm{ret}}$$

Total beam polarisation is the average polarisation of each beam electron.

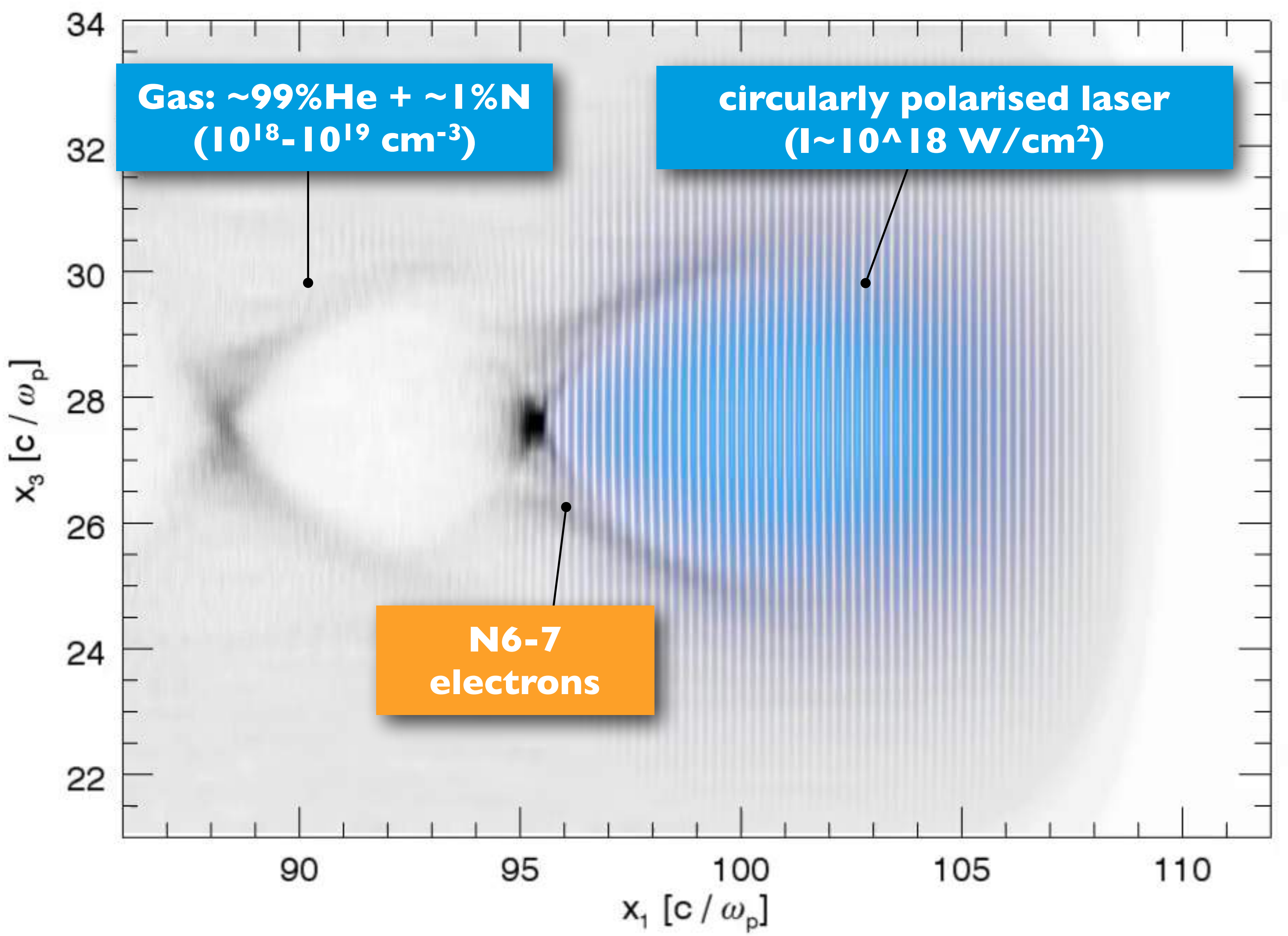
$$\langle P_c \rangle = \frac{1}{N} \Sigma_i P_i$$

Random phase approximation:
L. O. Silva *et al* Phys. Rev. E 59, 2273 (1999)

The angular momentum of light can exert a torque on relativistic plasma electrons

Ionisation injection with DLA

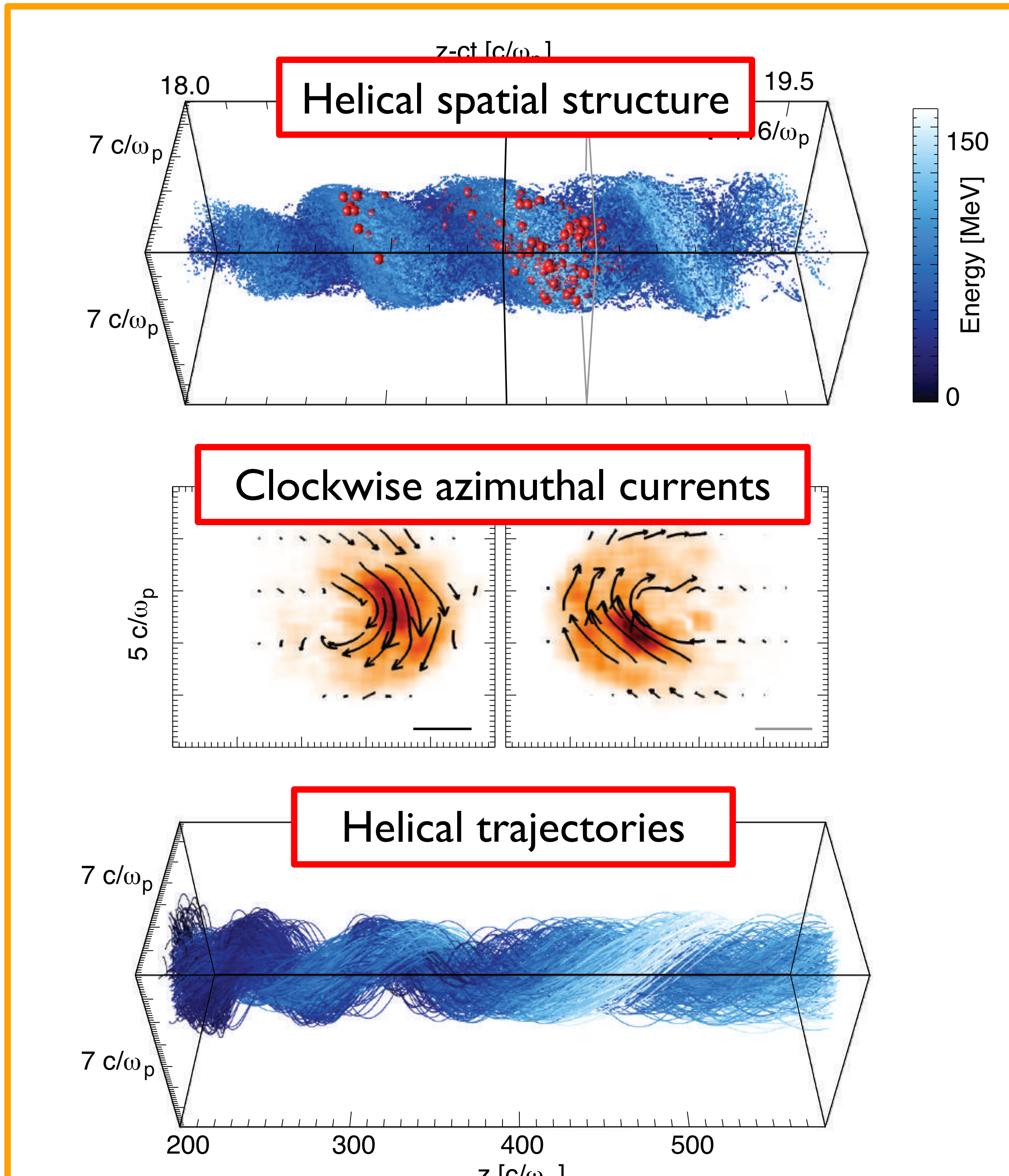
3D OSIRIS simulation with a mixture of Helium with Nitrogen



The laser modulates the outer Nitrogen shell electrons

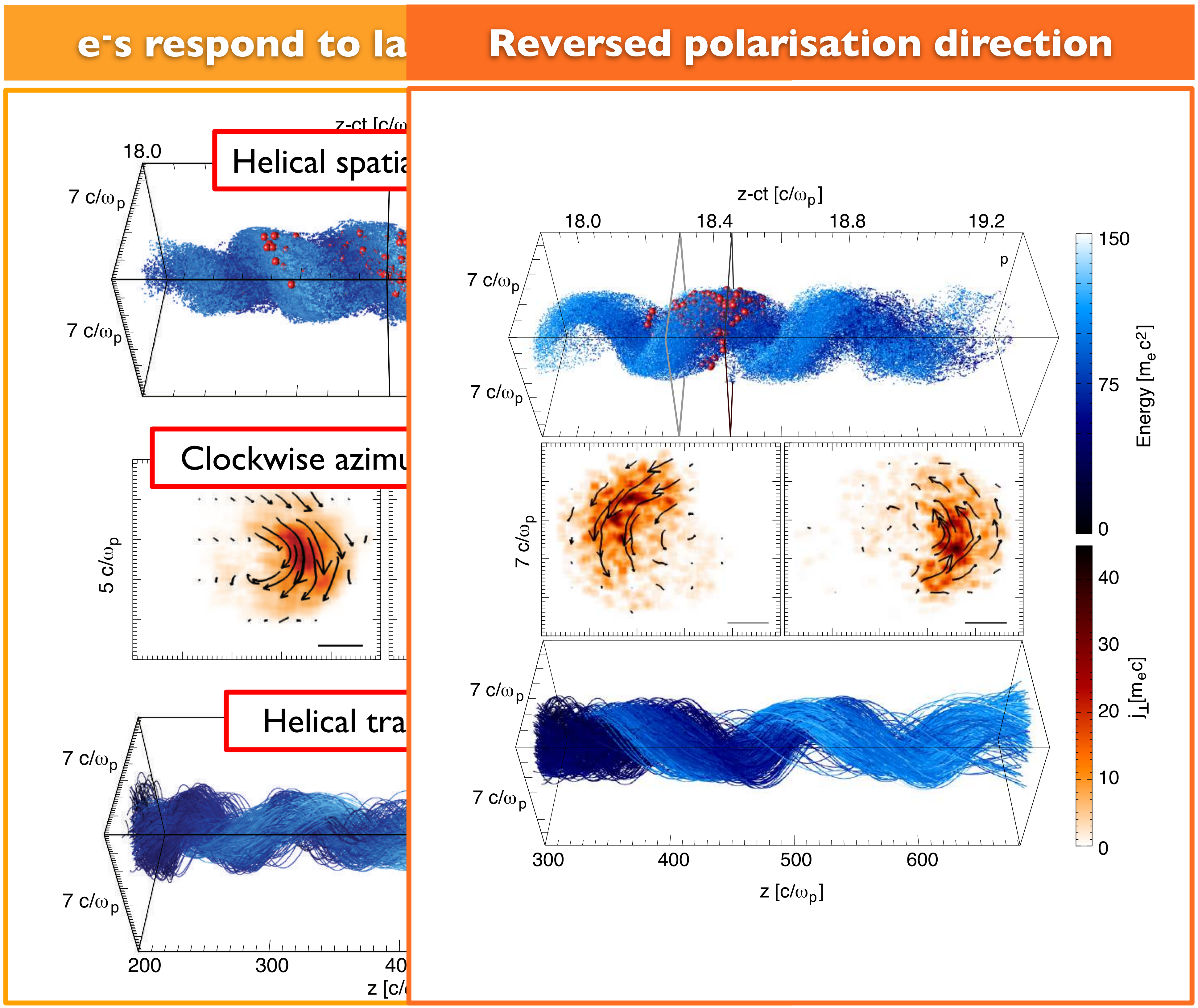
DLA leads to helical bunch currents and trajectories

e⁻s respond to laser polarisation



J Vieira *et al*, submitted (2016)

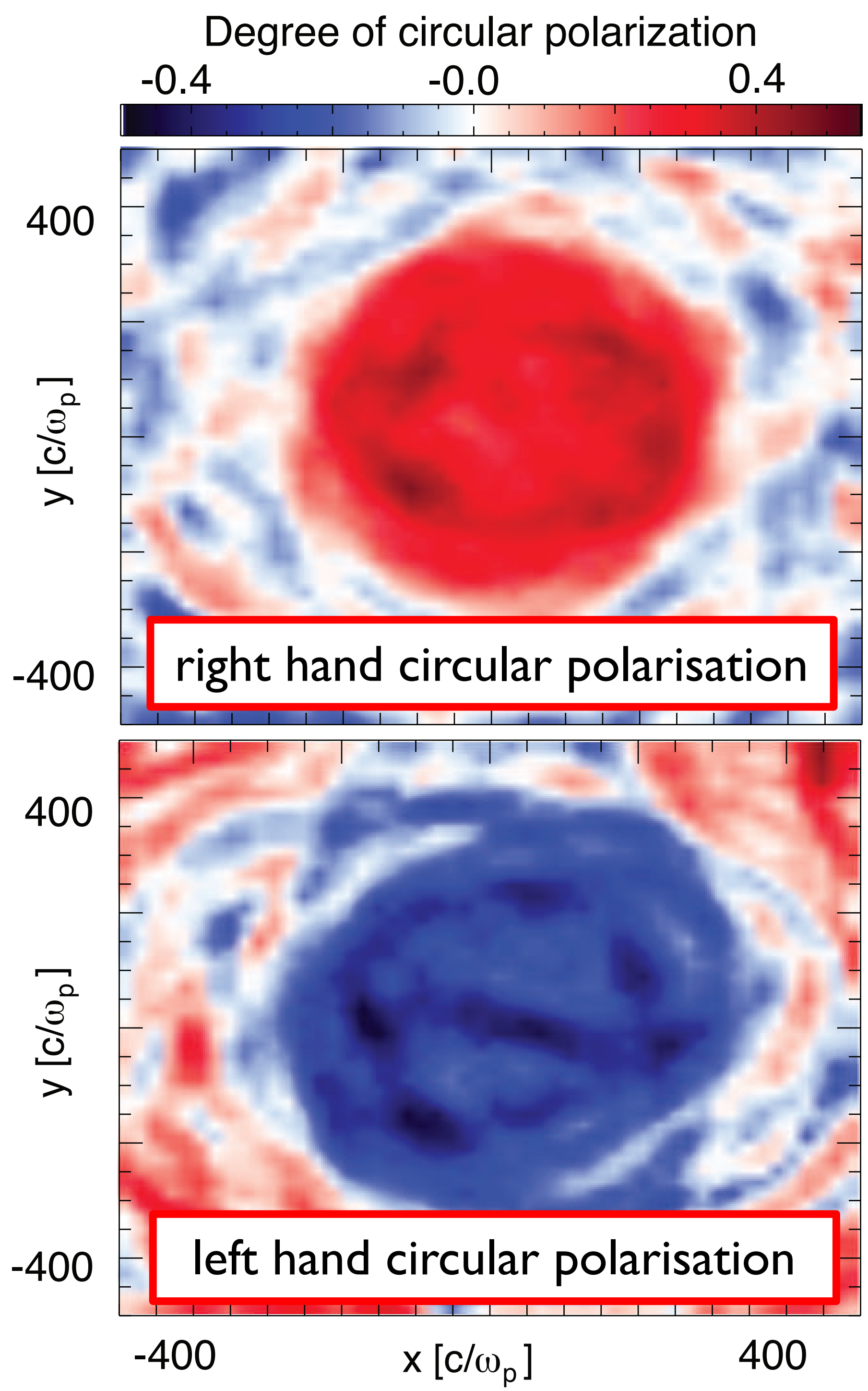
DLA leads to helical bunch currents and trajectories



J Vieira *et al*, submitted (2016)

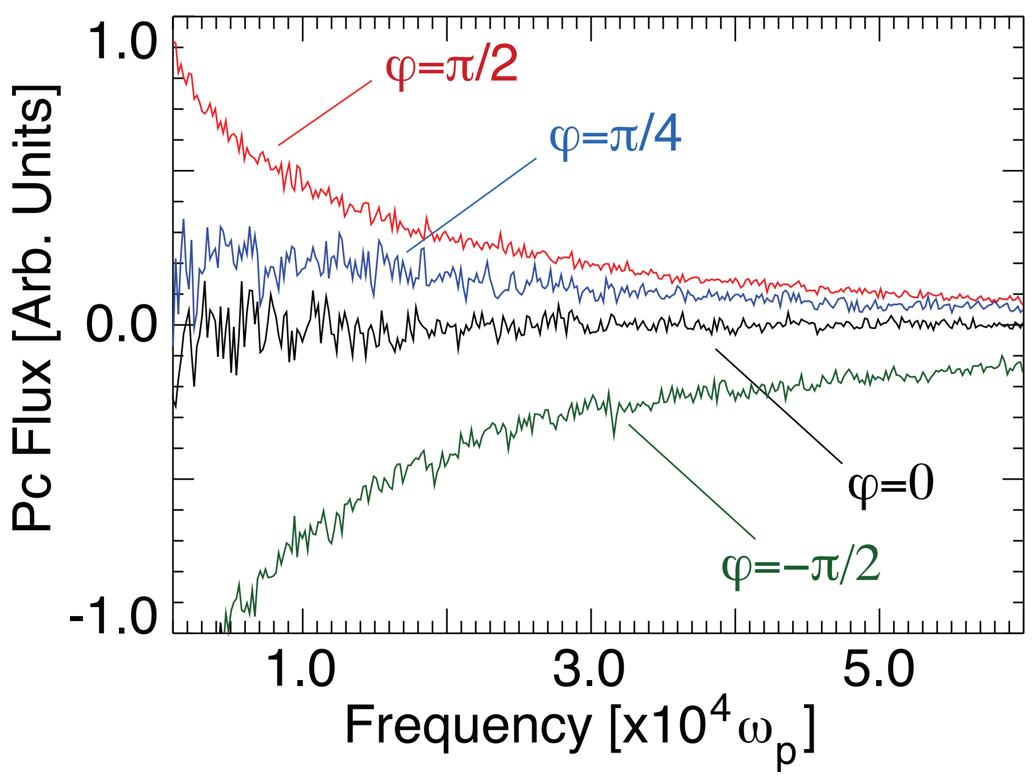
Betatron x-ray polarisation can be adjusted by driver polarisation

Circularly polarised x-rays



Polarisation control

φ is the phase difference between the two orthogonally polarised drivers



We may be able to control the **spin angular momentum** of x-ray photons for high energy density science

J Vieira *et al*, submitted (2016)

Contents

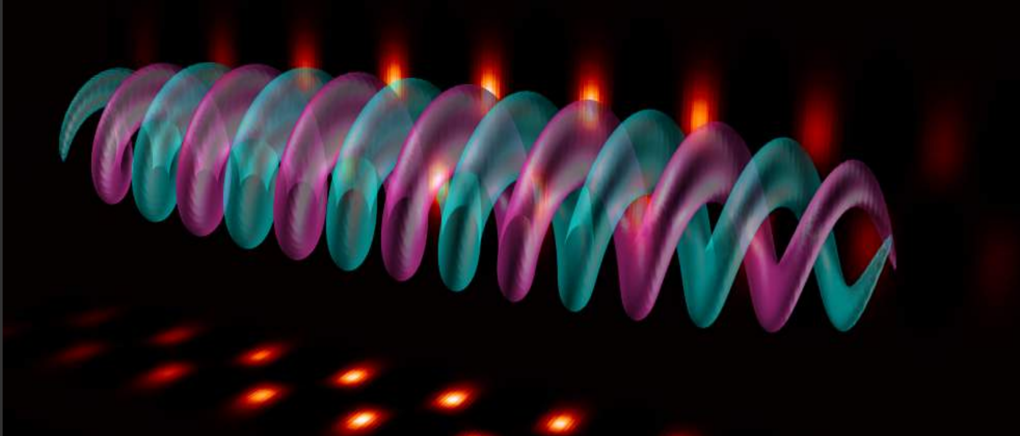
Lights' orbital angular momentum: a new twist for plasma accelerators

- Generation of circularly/elliptically polarised betatron x-rays
- Orbital angular momentum laser drivers for high gradient positron acceleration
- Radiation reaction and pair production driven by ultra-intense lasers
- Conclusions

The orbital angular momentum of light is an unexplored degree of freedom for laser-plasma interactions

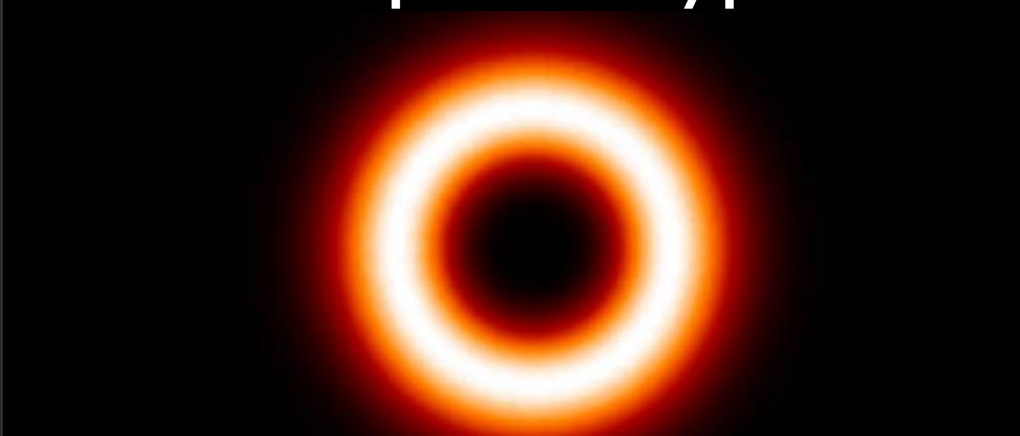
Production and amplification of OAM lasers in plasmas: J.Vieira, R.Trines *et al* Nat. Comms, accepted (2016)

Helical wavefronts



Laser electric field isosurfaces

Donut-shaped intensity profiles



Transverse slice of laser envelope

Laser-plasma accelerators

Shaped electron/x-ray beams

Ion acceleration (maybe reduce divergence)

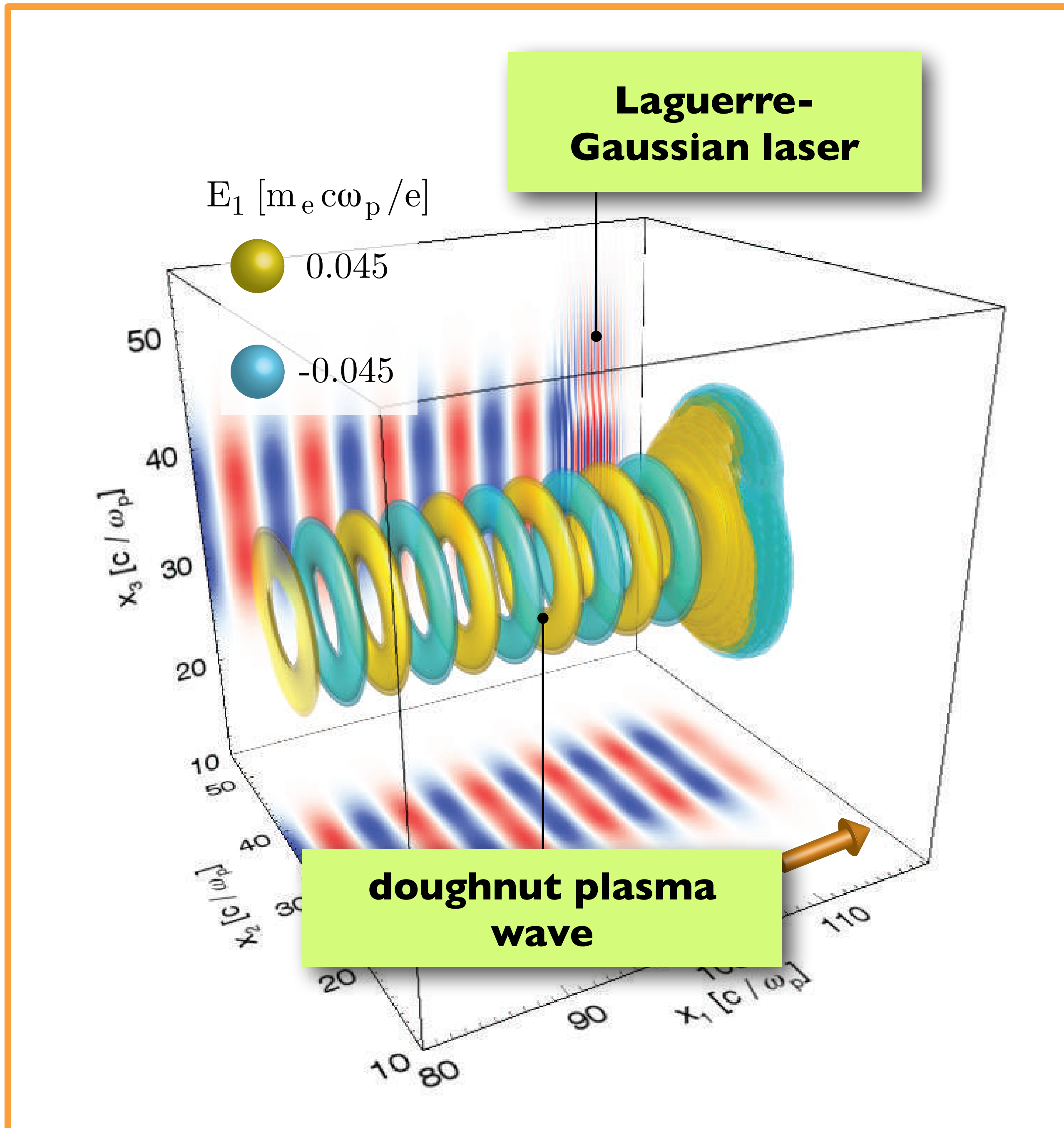
High gradient positron acceleration

Applications

- Astrophysics
- Ultrafast optical communications
- Nano particle manipulation

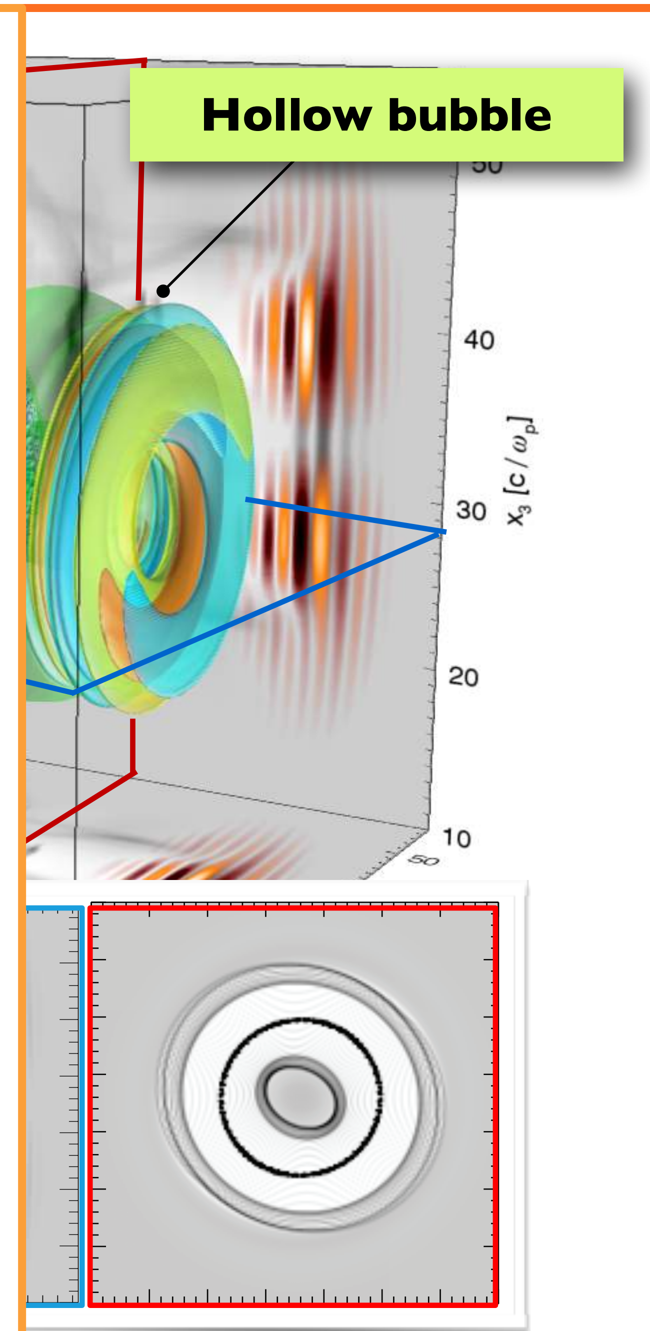
Laguerre-Gaussian lasers drive doughnut plasma waves in strongly non-linear regimes

Linear doughnut wakefields



J.T. Mendonça and J.Vieira, PoP **21**, 033107 (2014)

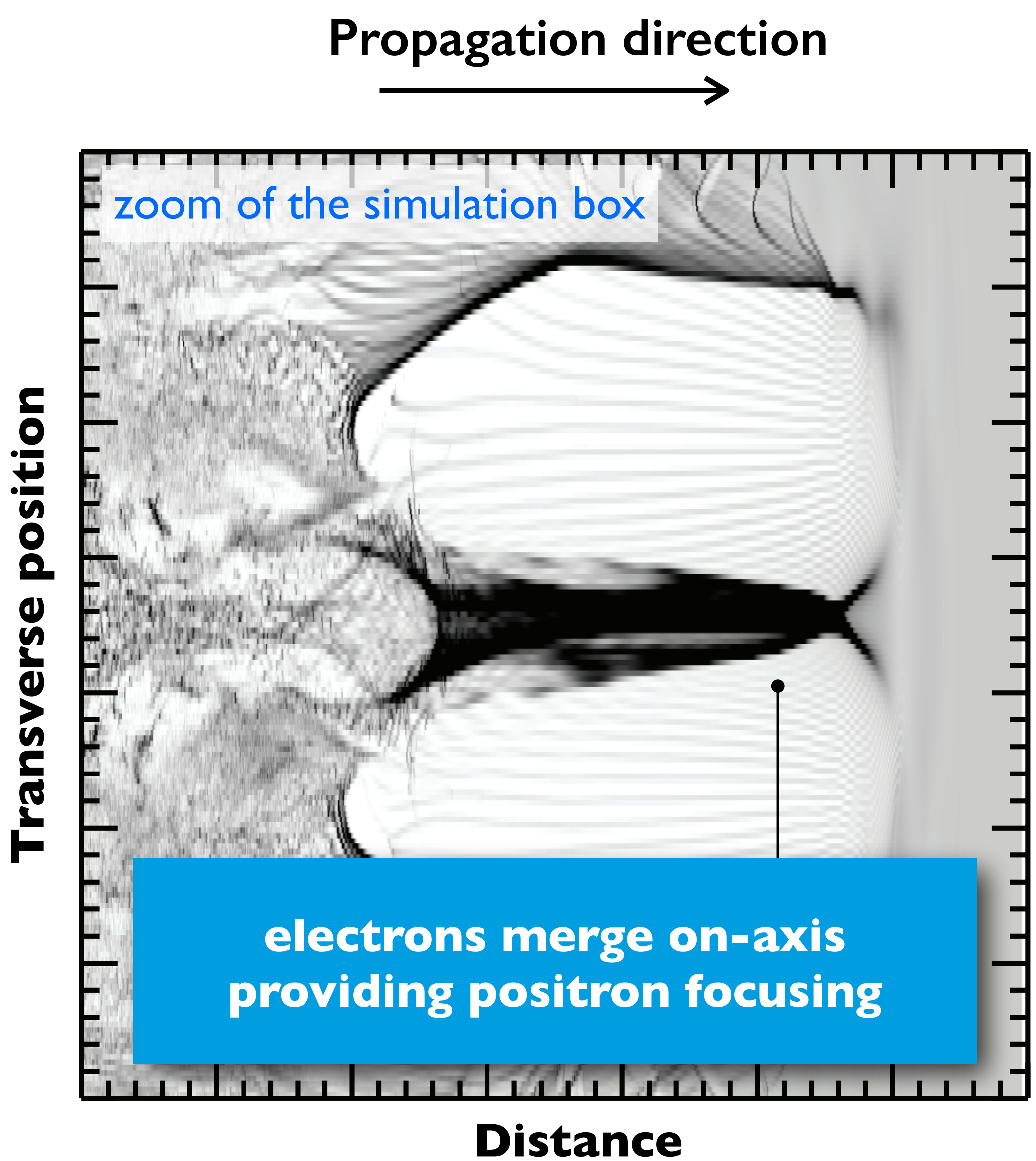
ughnut bubbles



a PRL **112**, 215001 (2014)

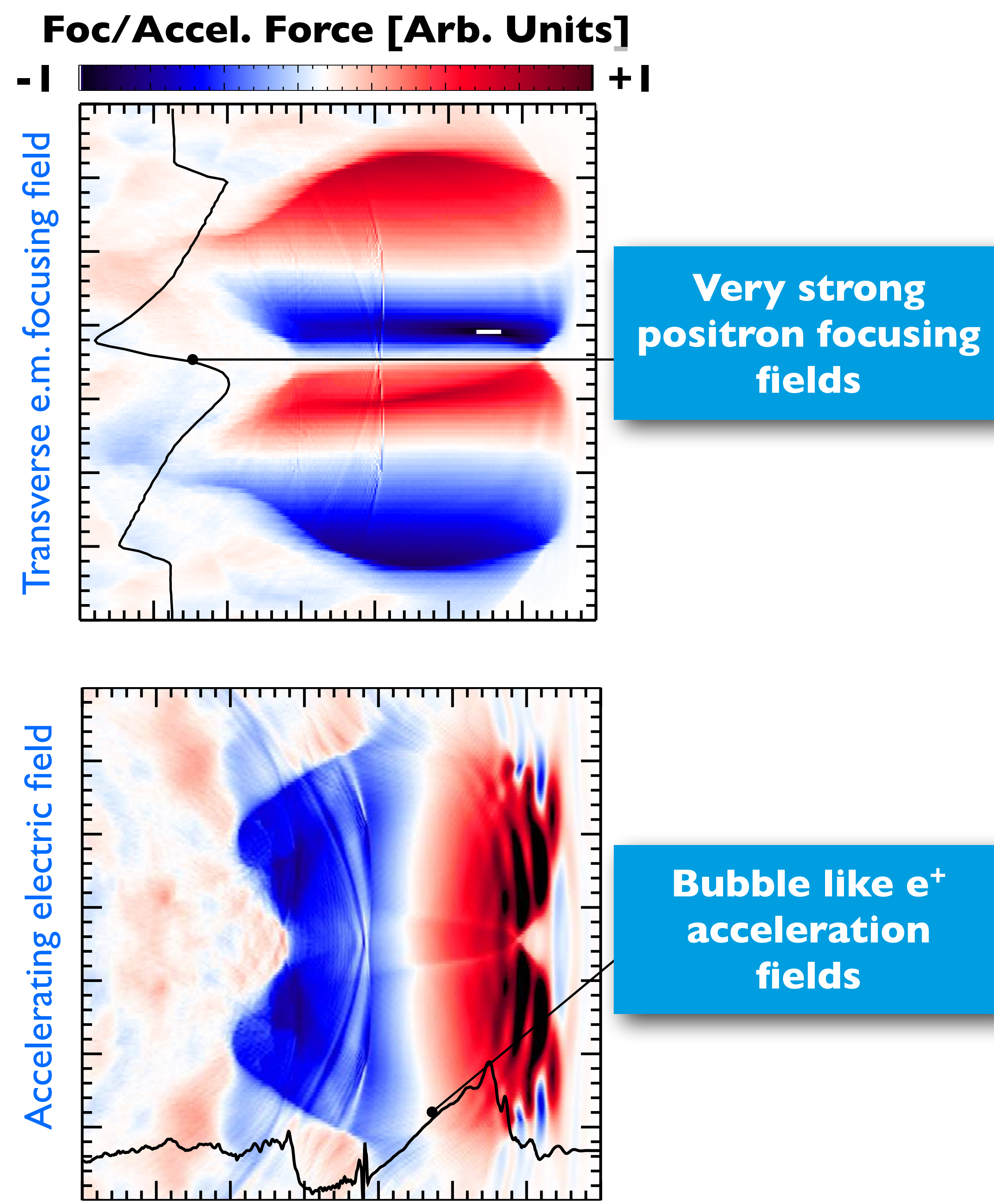
The onset of positron focusing and acceleration occurs when the inner sheath of the doughnut bubble merges on-axis

Onset of positron focusing



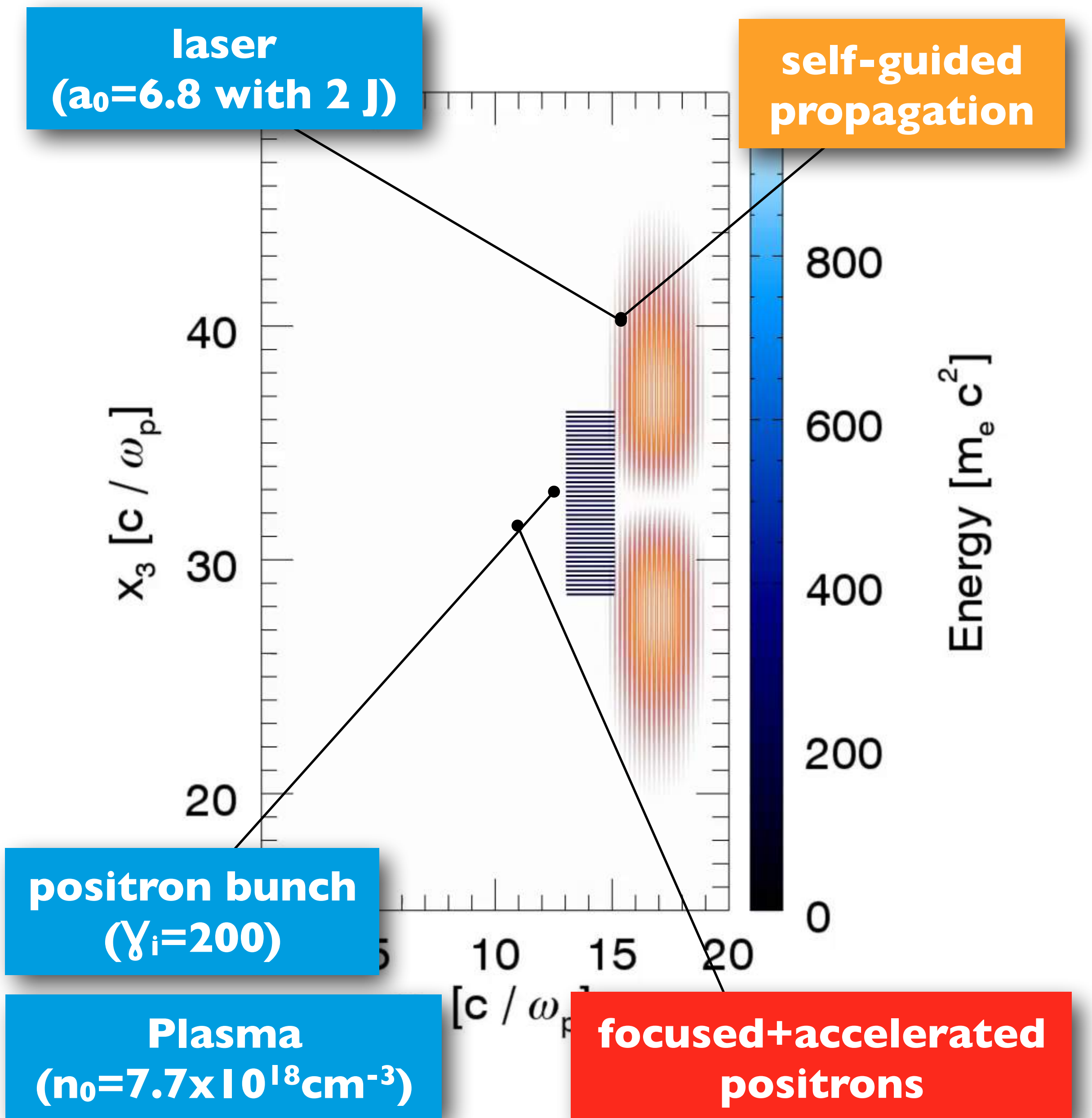
Similar physics when using linear combinations of TEM modes: **L.-L. Yu, C.B. Schroeder *et al.* PoP 21, 120702 (2014)**

e+ can accelerate at doughnut front

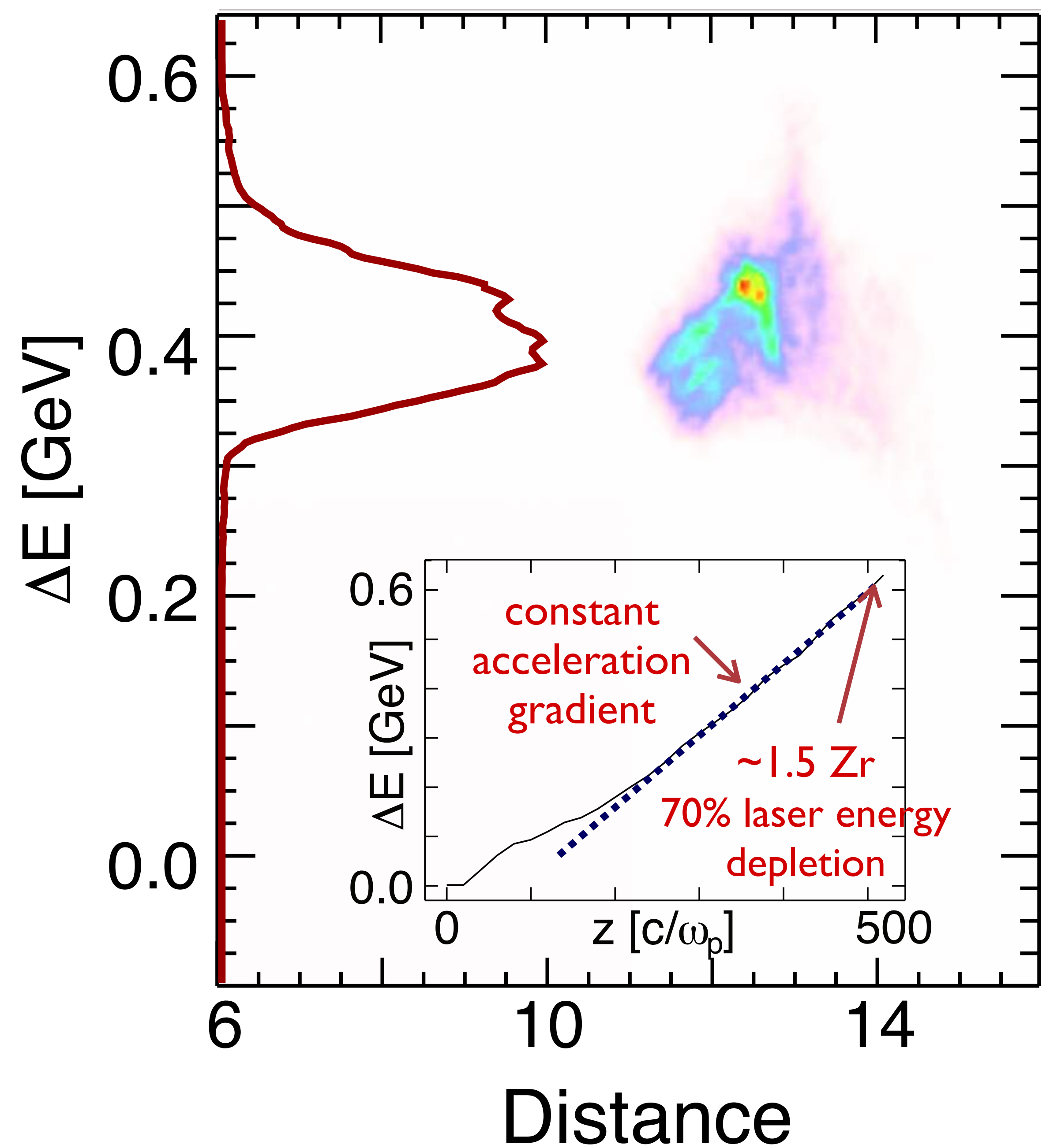


3D simulations show positron acceleration in strongly non-linear regimes

3D simulation of e+ acceleration



e+ bunch is quasi mono energetic

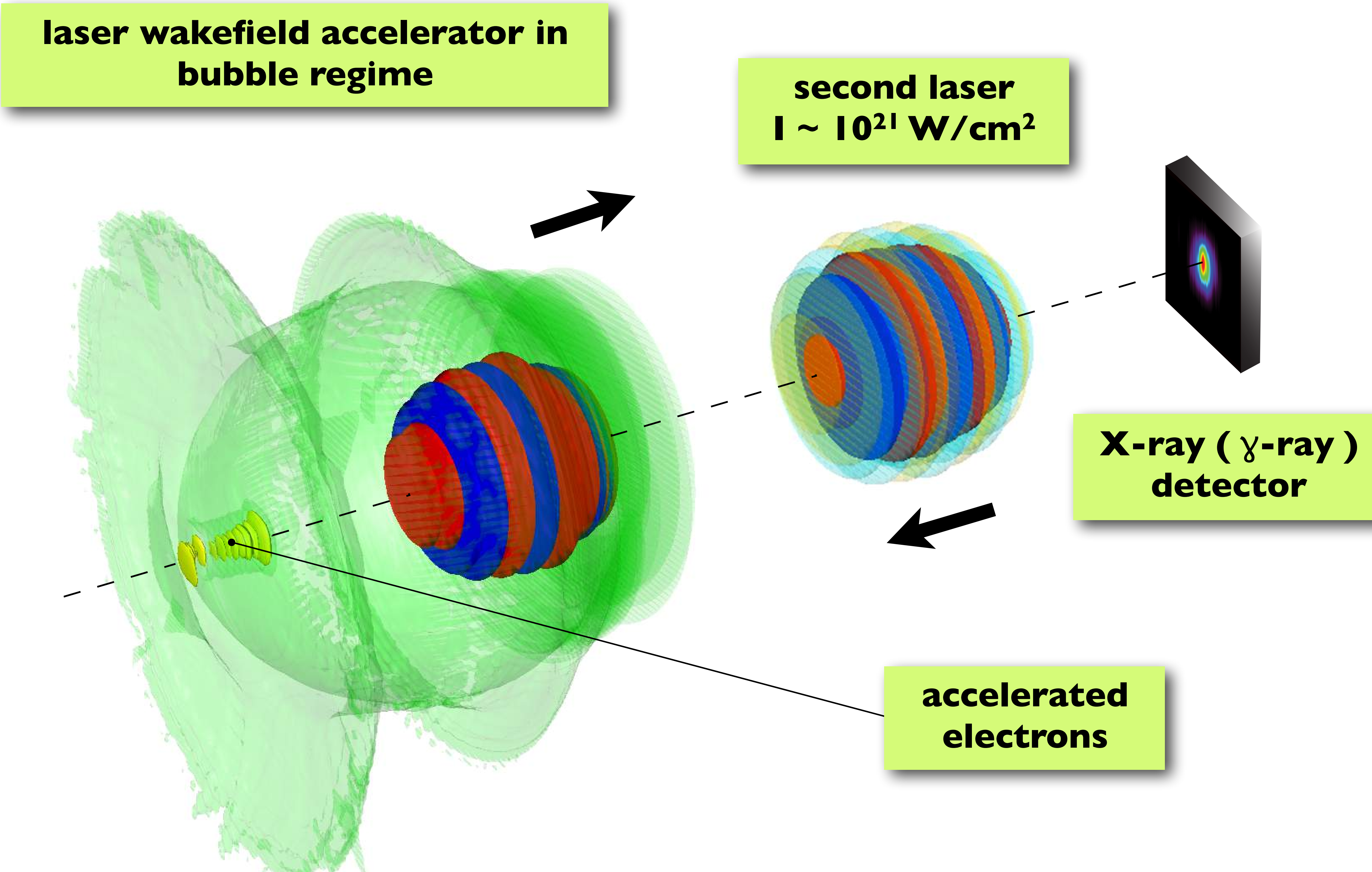


Contents

High field physics: when each single photon does matter in vacuum

All-optical radiation reaction configuration

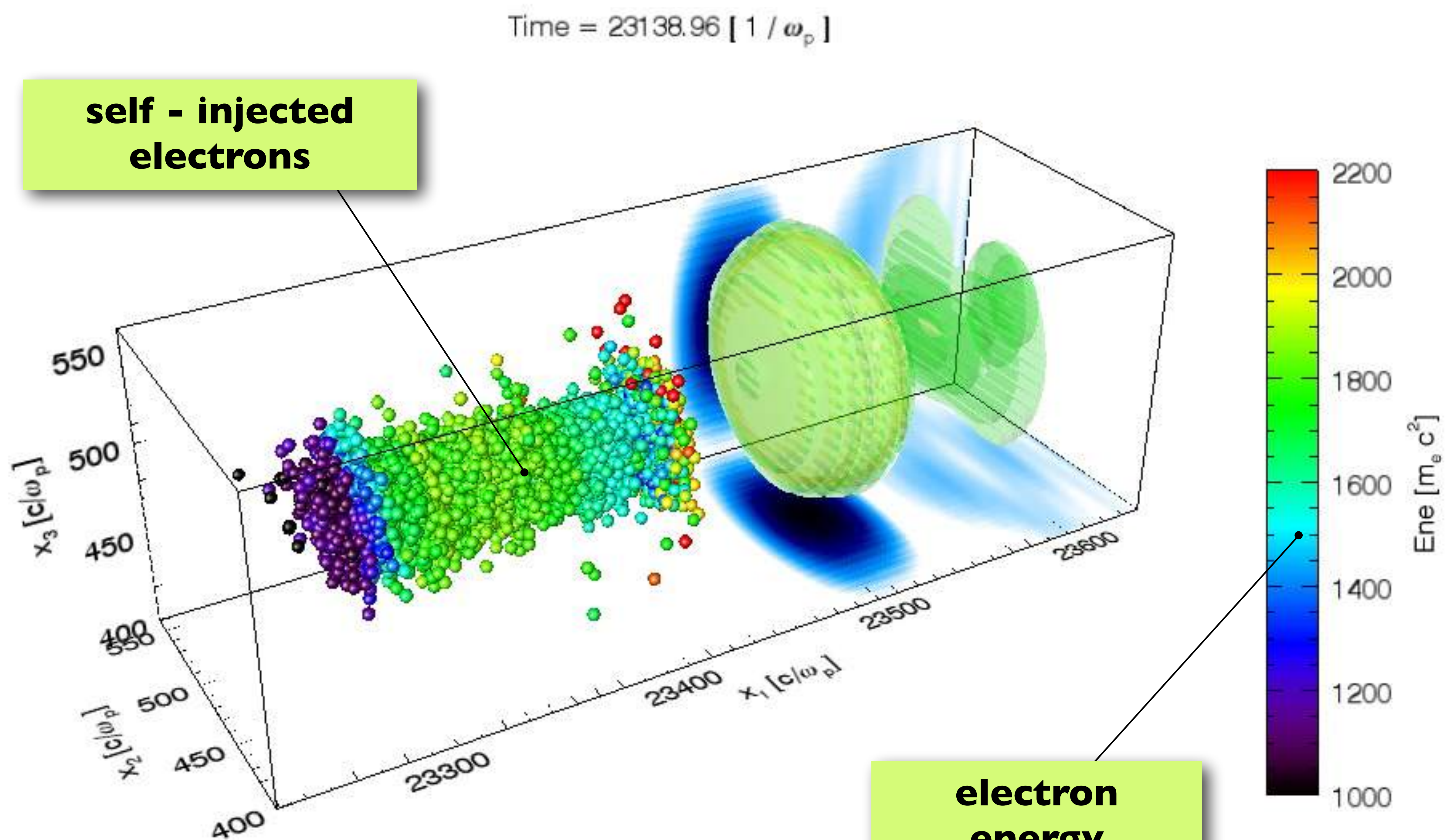
Identifying radiation reaction signatures in electron beam spectrum



M.Vranic *et al*, PRL 113, 1348001(2014)

Head-on collision in 3D with radiation reaction

LWFA electrons (1 GeV) lose energy in the interaction with an intense laser (10^{21} W/cm^2)

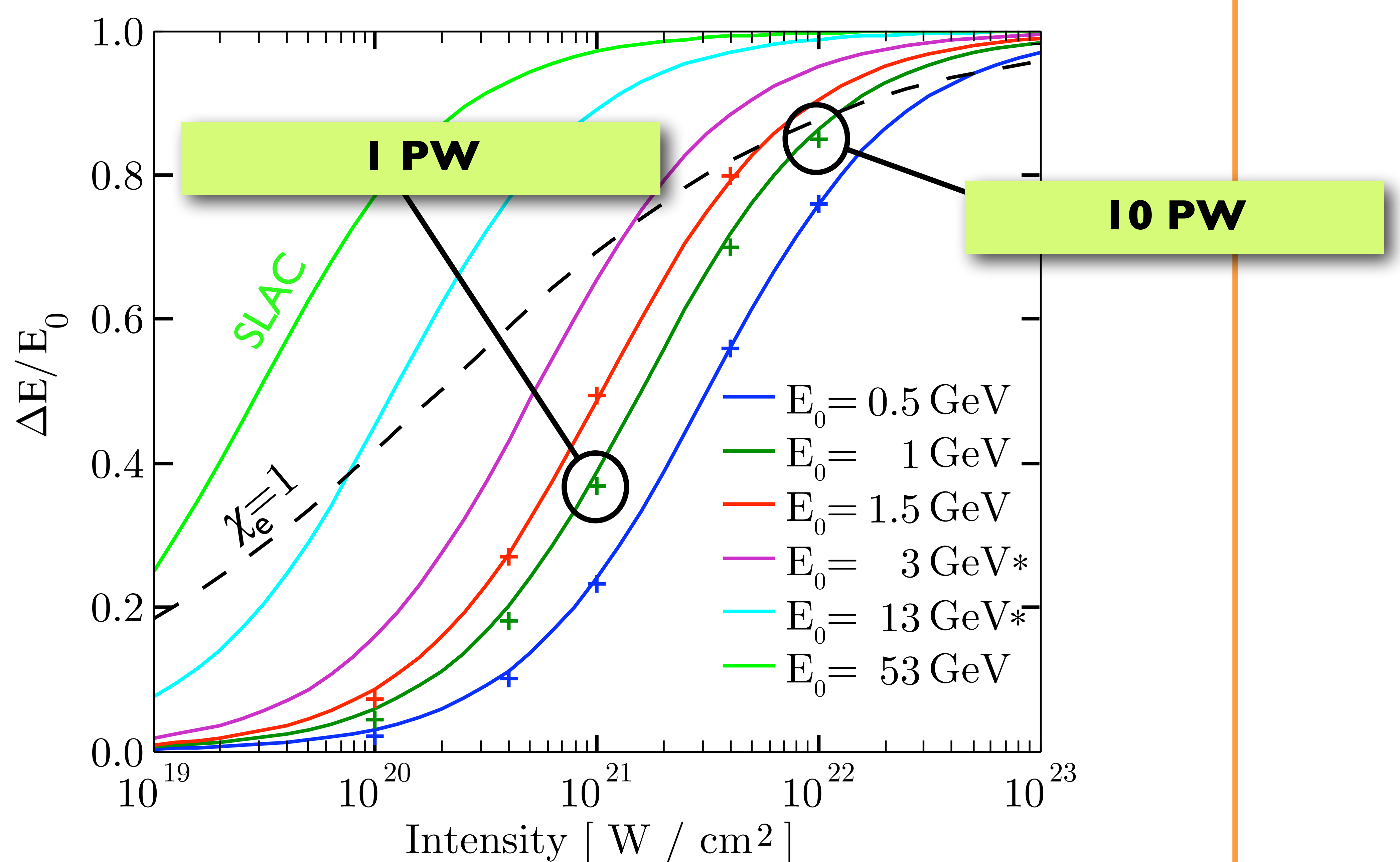


M. Vranic et al, PRL 113, 1348001(2014)

~40% energy loss for 1 GeV beam at 10^{21} W/cm^2

Radiation reaction can be tested with state-of-the-art lasers in this configuration

3D full-scale parameter scan



M. Vranic et al, PRL 113, 134800 1(2014)

Pairs can be produced already at χ = 0.6

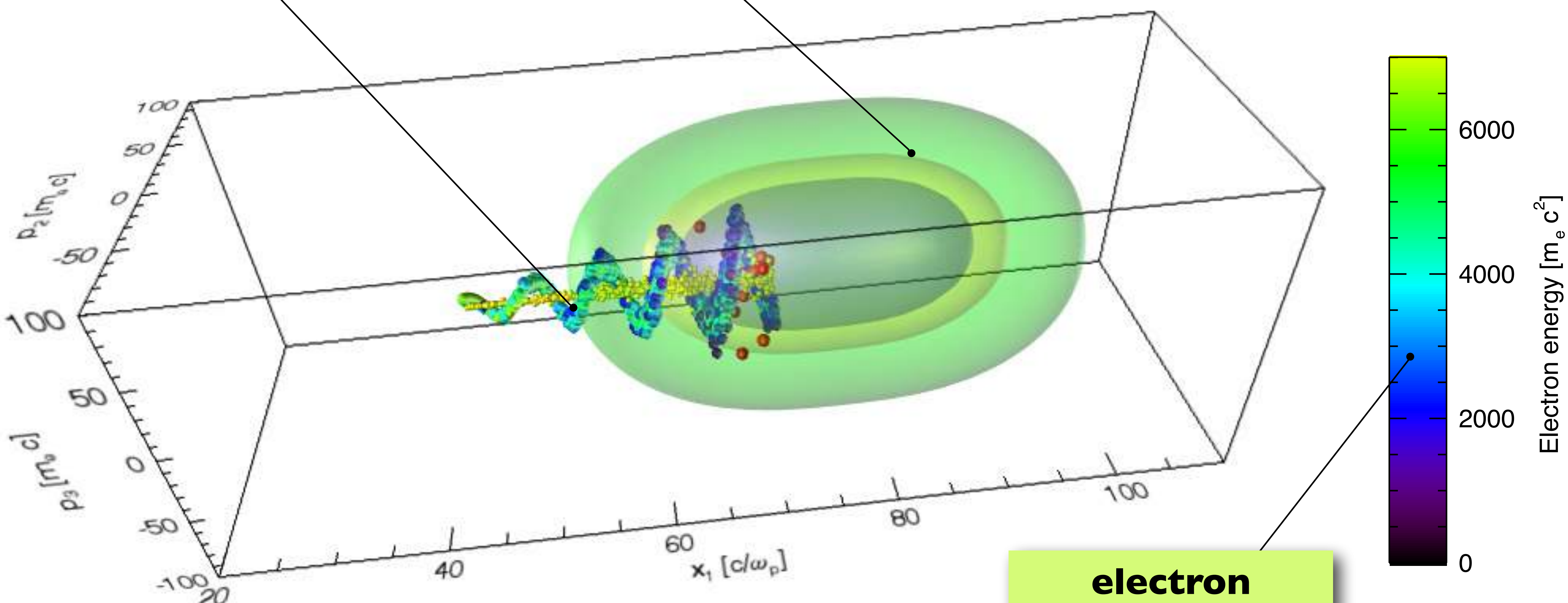
~ 200 pairs obtained per 1 000 000 interacting electrons

Parameters

laser I ~ 2x10^{21} W/cm^2, 30 fs, 1 um
electron initial energy ~ 3 GeV

- electron
- positron
- photon

interacting laser



electron energy

Simulations performed by M. Vranic and T. Grismayer

Electron beam energy spread and divergence:

M. Vranic *et al* ArXiv1511.04406; submitted to NJP (2016)

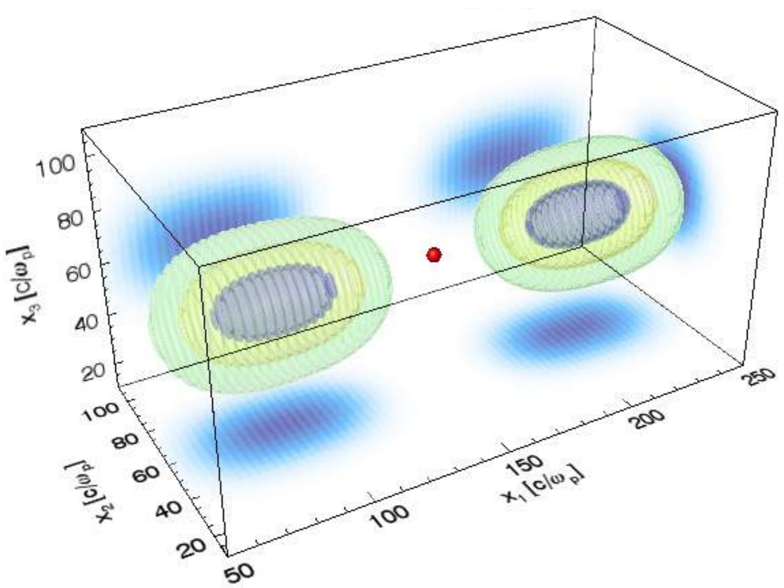
3D OSIRIS QED - colliding laser cascades at $\chi \gtrsim 1$

T. Gris. Grismayer, M.Vranic

Linear

Laser parameters

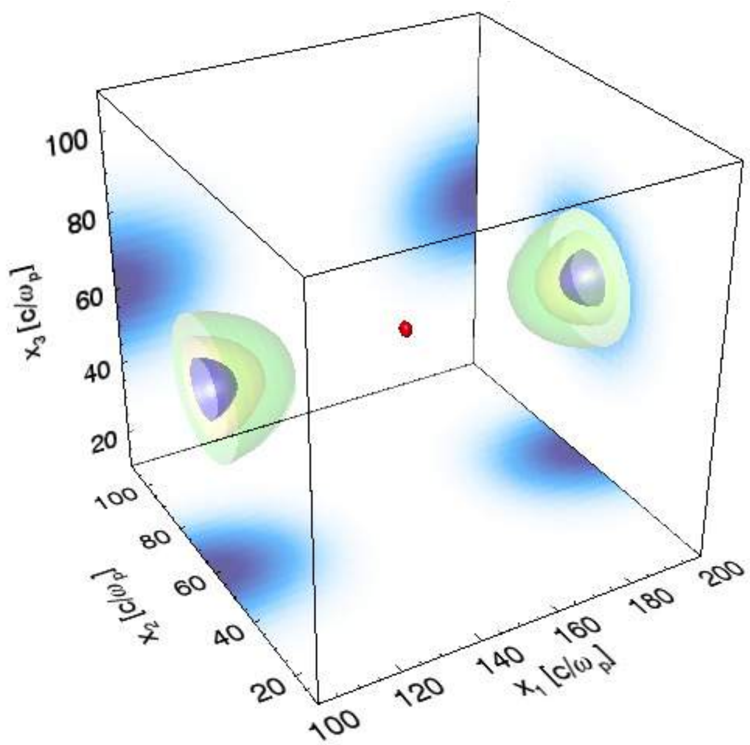
- a_0 = 1000, λ = 1 um,
- τ = 30 fs, W_0 = 5 um



Particles remain in the x_1-x_2 plane

Double clockwise

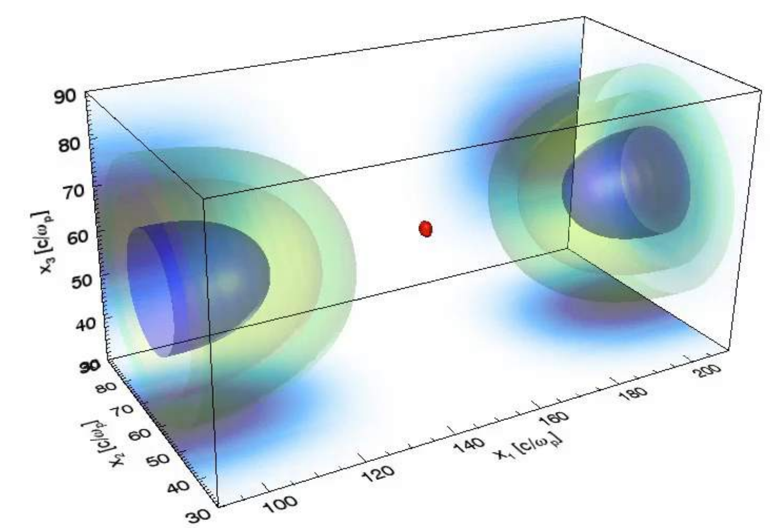
- electron
- positron
- photon



Particles explore the whole space

Clockwise-anti clockwise

- electron
- positron
- photon

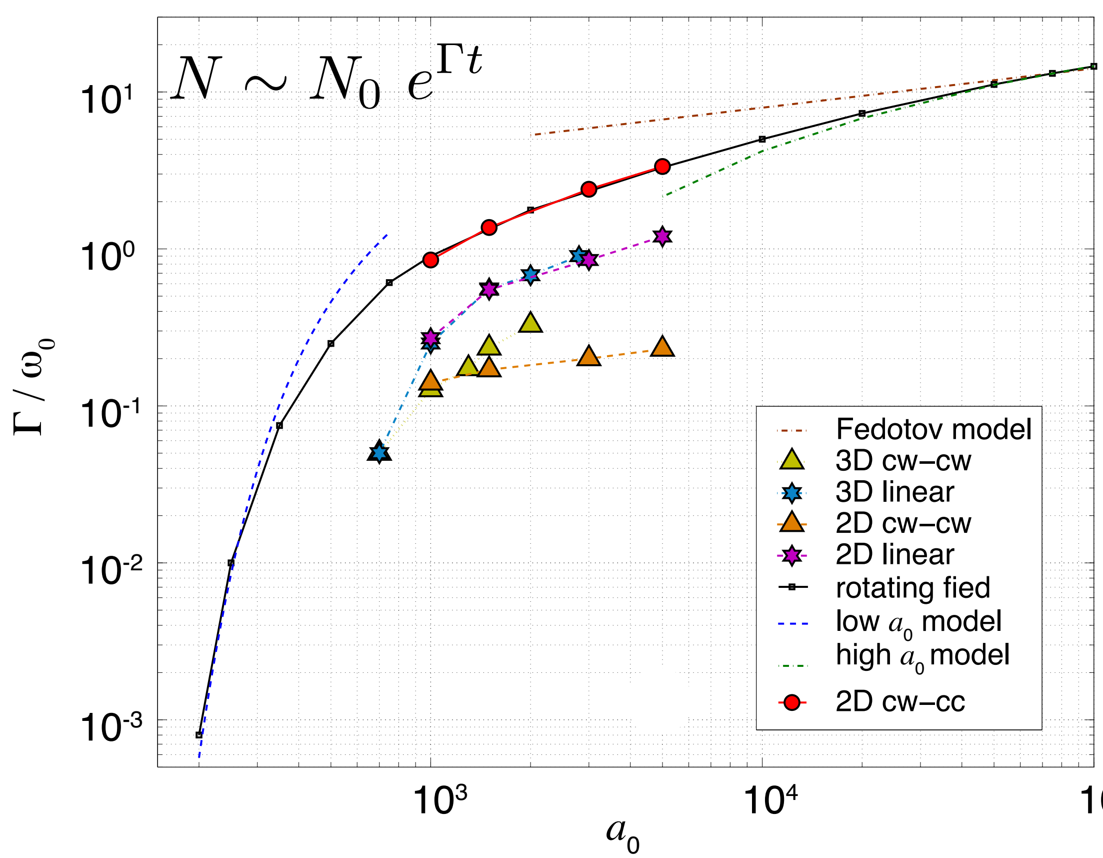


Particles rotate mainly in the x_2-x_3 plane

QED cascades - from the seed to full laser absorption

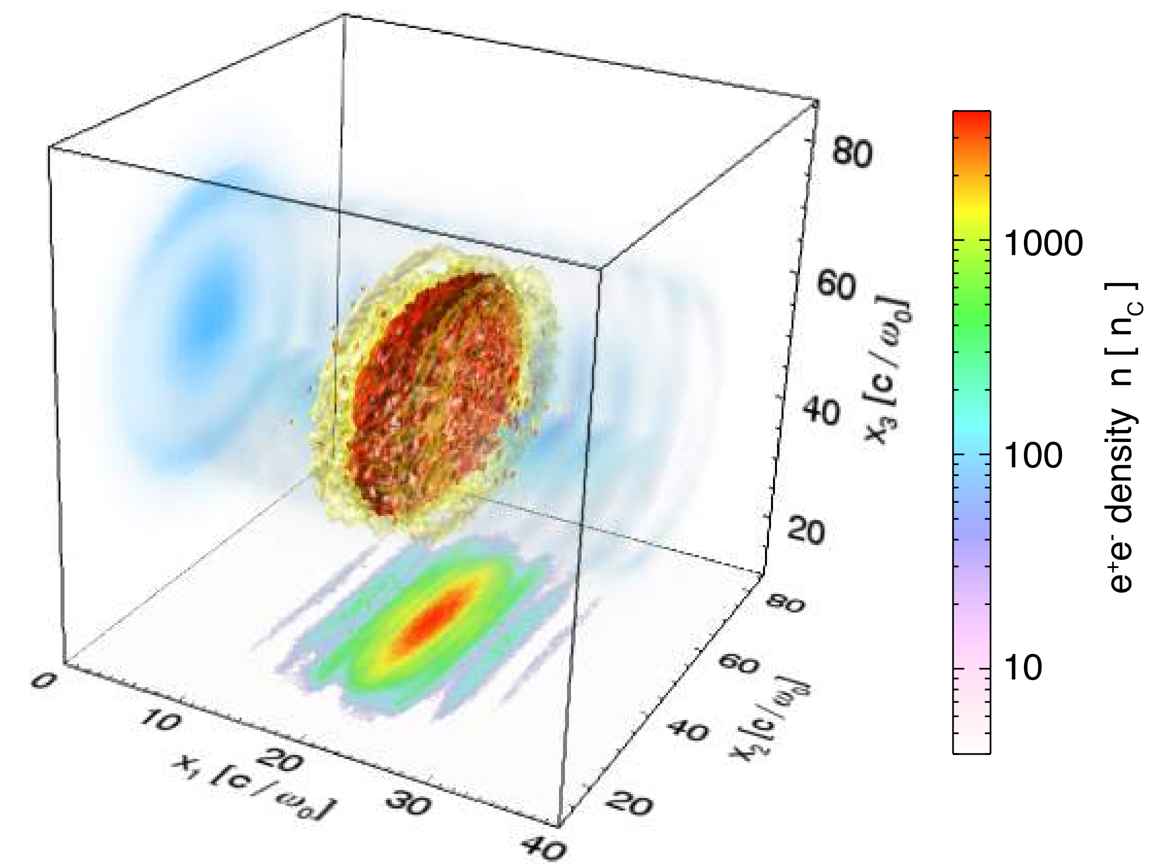
Analytical growth rate model + 3D full scale parameter scan

T. Grismayer, M.Vranic et. al,
Submitted to PRL,
ArXiv: 1511.07503



Laser absorption via QED cascades absorption model + 2D, 3D sim.

T. Grismayer, M.Vranic et. al,
Submitted to POP (APS invited paper),
ArXiv: 1512.05174

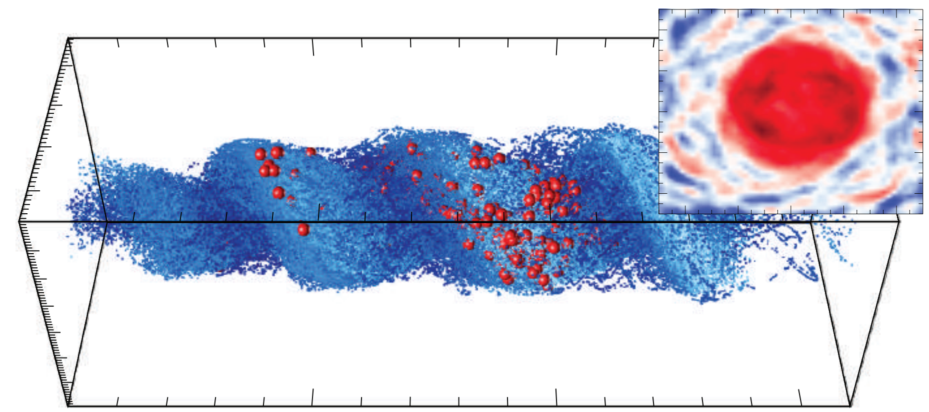


Contents

Conclusions

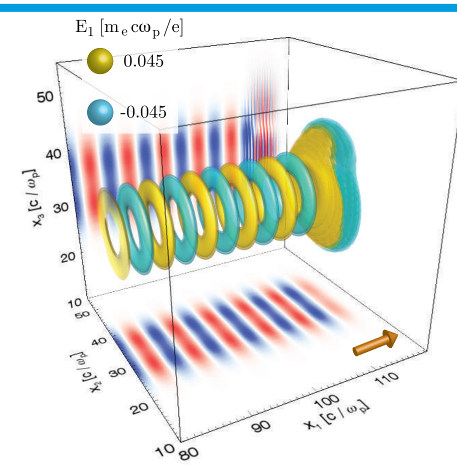
Betatron radiation polarisation control

- Circular/elliptical polarisation can be produced in the x-rays
- Level of polarisation controlled by laser driver polarisation
- **Could be tested from Phase I onwards**



Twisted lasers for LWFA

- Production of exotic particle beams with non-trivial dynamics
- High gradient positron acceleration
- **Could be tested in phase I**



High field physics

- Radiation reaction can be observed with today's lasers
- Pair production can be achieved with BELLA-i parameters
- **Could be tested in Phase II-III**